Photorecombination and Photoionization Experiments at Heavy-Ion Storage-Rings and Synchrotron-Light Sources

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Abstract. Recent experimental work on the photorecombination and the photoionization of astrophysically relevant atomic ions employing the merged-beams technique at heavy-ion storage-rings and synchrotron-light sources, respectively, is summarized. The resulting *absolute* photoionization cross sections and recombination rate coefficients benchmark corresponding theoretical calculations and are needed for the accurate determination of ionization equilibria in astrophysical plasmas.

1. Introduction

Photoionization (PI) and Photorecombination (PR) are basic atomic processes which govern the charge state balance in any plasma. Therefore, the accurate knowledge of these processes is a prerequisite for any plasma modeling and, hence, for any meaningful interpretation of many astrophysical observations. To date most PI and PR cross sections used in plasma modeling stem from theoretical calculations. Their accuracy is often difficult to asses and, therefore, experimental PI and PR cross sections and rate coefficients are vitally needed as benchmarks and guidelines for the development of the theoretical methods. Moreover, in the near future experiments will probably be the only reliable source for PR and PI cross sections of complex ions such as ions with an open M-shell (Schippers et al. 2002a; 2003a).

The measurement of PR and PI cross sections of atomic (and molecular) ions is experimentally challenging because the ion densities which can experimentally be prepared are very low — some 10^6 cm^{-3} (to be compared with $\sim 10^{13}$ cm^{-3} for gaseous and $\sim 10^{22}$ cm^{-3} for solid targets). Consequently, signal rates from electron-ion and photon-ion collision experiments are comparatively weak. In order to make up for the low ion density in such experiments an arrangement is chosen where the colliding particle beams are merged collinearly over a distance of the order of 1 m. The merged-beams arrangement (Phaneuf et al. 1999) provides a relatively large interaction volume, and the directionality of the ion beam facilitates the effective collection of the PI or PR reaction products, i.e., of ions which have changed their charge state due to either ionization or recombination. For the measurement of *absolute* PR and PI cross sections the merged-beams method was implemented at heavy-ion storage rings (Müller & Wolf 1997; Müller & Schippers 2001) and at synchrotron-light sources (West 2001; Covington et al. 2002), respectively.

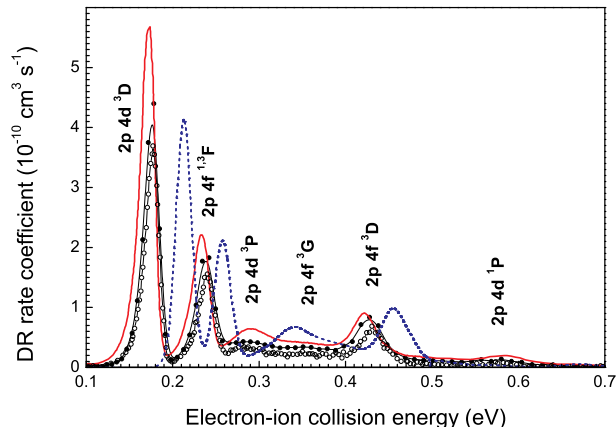## 2. Photorecombination of atomic ions

Figure 1.   Dielectronic recombination (DR) of $C^{3+}(1s^2\,2s)$-ions at low energies: experiment (full symbols: Schippers et al. 2001, open symbols: Mannervik et al. 1998), many body perturbation theory (full line: Mannervik et al. 1998) and Breit-Pauli R-Matrix theory (dashed line: Pradhan et al. 2001).

The basic procedure for producing plasma rate coefficients from PR measurements at storage rings was outlined by Müller (1999). Recent examples are the PR rate coefficients of the lithiumlike ions C IV (Schippers et al. 2001), O VI (Böhm et al. 2003) and Ni XXVI (Schippers et al. 2000). Figure 1 shows a comparison between measured and calculated C IV dielectronic recombination (DR) rate coefficients at low electron-ion collision energies. The two experimental results, which were obtained a two different storage-rings, agree with one another to within the 15% experimental error for the absolute cross section. This exemplifies the reliability of recombination measurements at storage rings. Mannervik et al. (1998) also calculated the C IV DR rate coefficient using relativistic many-body perturbation theory (RMBPT, Tokman et al. 2002). They pointed out that even for a light ion such as C IV, a *relativistic* treatment of the recombination process is necessary to reproduce the experimentally observed $2p\,4l$ DR resonance structure. Presently, RMBPT is only applicable to relatively simple systems and it is therefore instructive to see in how far more standard "production" codes are able to reproduce low-energy resonance positions and strength. For C IV the Breit-Pauli R-Matrix results of Pradhan et al. (2001) are only up to 20 meV off the measured resonance positions (figure 1). It should be kept in mind, however, that there are pathological systems, e. g. Mg IX, where a mere 50 meV uncertainty of low-energy resonance positions can translate into a nearly one-order-of-magnitude uncertainty on the plasma rate-coefficient scale in a temperature range where the ion is expected to form in photoionized gases (Schippers et al. 2004). Such findings strongly emphasize the need for experimental benchmarks, especially for low-temperature PR rate coefficients.

Photorecombination measurements responding to astrophysical data needs were carried out for L-shell iron ions at the Heidelberg storage-ring TSR by

Savin et al. (1997; 1999; 2002a; 2002b; 2003) who already published DR rate coefficients for the ions Fe XVIII through Fe XXII. In a series of measurements with lithiumlike ions the influence of external electromagnetic fields on DR cross sections was thoroughly investigated by Bartsch et al. (1997; 1999; 2000), Böhm et al. (2001; 2002) and Schippers et al. (2000). This work is also of astrophysical interest. It was recently summarized by Müller & Schippers (2003).
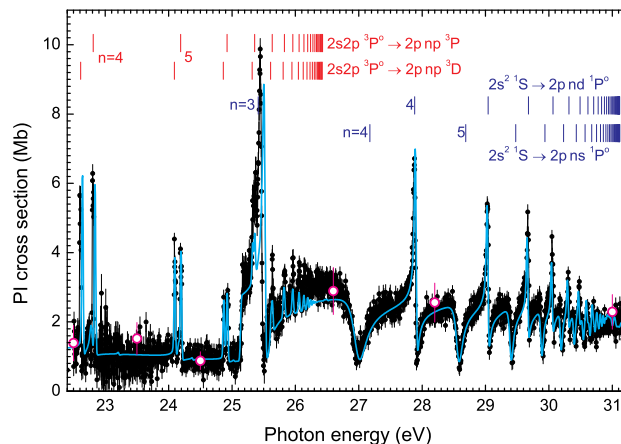
3. Photoionization of atomic ions

Figure 2. Photoionization of B^+-ions: experiment and Breit-Pauli R-Matrix theory (Schippers et al. 2003b). From the comparison between experiment and theory it is concluded that 29% of the ions in the experiment were in the metastable state.

More recently experiments aiming at measuring absolute PI cross sections of atomic ions and employing merged photon-ion beams were set up at 3rd generation synchrotron light sources. Measurements of astrophysical relevance were carried out e. g. for singly charged boron (figure 2, Schippers et al. 2003b), carbon (Kjeldsen et al. 2001), nitrogen (Kjeldsen et al. 2002a), oxygen (Covington et al. 2001; Kjeldsen et al. 2002a; Aguilar et al. 2003a), neon (Covington et al. 2002), magnesium (Kjeldsen et al. 2000; Aguilar et al. 2003b) and iron (Kjeldsen et al. 2002b) as well as for the multiply charged ions C III (Müller et al. 2002), Ne IV (Aguilar 2003c), and Al III (Aguilar et al. 2003b).

Finally, it should be mentioned that the possibility to relate the time-inverse processes of PI and PR via the principle of detailed balance can be exploited for consistency checks between PI and PR measurements (Müller et al. 2002) and to obtain more comprehensive results than from only one experiment alone (Schippers et al. 2002b, 2003a).

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